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FRACTURE TOUGHNESS AND STRESS CORROSION CHARACTERISTICS OF ULTRAHIGH-STRENGTH 4340 STEEL - SUMMARY REVIEW

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ABSTRACT

A review was made of the fracture toughness (K_{Ic}) and stress corrosion (K_{Iscc}) characteristics of 4340 steel within the 200 to 250 ksi yield strength range. This literature review was conducted in support of a fracture mechanics and environmental investigation of 4340 steel for the control section housing of the Copperhead CLGP (Cannon-Launched Guided Projectile) weapon system. Factors affecting toughness and corrosion cracking characteristics are considered. Also included are data pertaining to the damaging effects of humidity. Fracture toughness and stress corrosion cracking resistance of 4340 steel are usually higher in the alloys possessing lower yield strengths.

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INTRODUCTION

Background

Continued advances in weapons technology reiterate the need for ultrahigh-strength materials. Reliability, minimum weight, and economy are important requirements for guided missile components. These components must be fabricated from materials possessing high strength:weight ratios as well as uniform and reproducible mechanical properties such that unexpected failures will not occur at stresses lower than the design operating conditions. If strength of material was the only limiting design parameter, it would be a simple procedure to select a strong material for application. Unfortunately, many widely used engineering alloys experience failure at nominal stress levels well below their yield strengths when exposed to particular conditions of temperature, loading rate, stress distribution, and surrounding enviornment.

Fracture Toughness Considerations

To mitigate these problems, designers are increasingly employing linear elastic fracture mechanics principles and concepts of crack-extension force and stress intensity factor in their utilization of high strength materials. As a consequence of much research activity and rapid development,[1-3] fracture toughness testing, based on fracture mechanics principles, has quickly evolved from the research stage to a standardized procedure.[4] Of growing interest at this time is the true material property of plane strain fracture toughness designated as K_{Ic}. Failure in a structure can occur when the stress intensity K equals the fracture toughness value.

Stress Corrosion Considerations

Since weapon system components are often stored in readiness condition for long periods of time in controlled or uncontrolled environments, stress corrosion cracking susceptibility must be considered. Stress corrosion cracking (scc) is the failure of material from the combined effects of a corrosion environment and a static tensile stress. The source of the stress may be from applied loads or "locked-up" residual stresses.

Fracture mechanics can also be employed in the analysis of stress corrosion cracking.[5,6] The threshold value of stress intensity is designated K_{Iscc}. Crack growth should not occur for stress intensities K below K_{Iscc}. If an initial value of K is above K_{Iscc}, existing cracks can be expected to grow with time until fracture occurs.

1. *Fracture Toughness Testing and Its Applications.* ASTM STP 381, 1965.
2. *Plane Strain Crack Toughness Testing of High Strength Metallic Materials.* ASTM STP 410, 1966.
3. *Review of Developments in Plane Strain Fracture Toughness Testing.* ASTM STP 463, 1970.
4. ASTM Test for Plane-Strain Fracture Toughness of Metallic Materials: E399-74.
5. SCULLY, J. C., ed. *The Theory of Stress Corrosion Cracking in Alloys.* NATO Science Committee, Research Evaluation Conference, Brussels, W. S. Maney and Sons, Ltd., Leeds, England, 1971.
6. BROWN, B. F., ed. *Stress Corrosion Cracking in High Strength Steel, Titanium, and Aluminum Alloys.* U. S. Government Printing Office, Stock No. 0851-0058, 1972.

Application

The Copperhead CLGP (Cannon-Launched Guided Projectile) weapon system is a high-performance 155-mm laser-guided projectile. Its control section housing component is basically the outer skin of the projectile from the warhead to the aft closure and is fabricated from air-melted, vacuum-degassed 4340 steel. This component is eventually heat treated to Rockwell C 53 to C 55 hardness range.

Objective

Fracture mechanics principles are being used to analyze the control section housing, and tests have been initiated to determine the fracture toughness and other mechanical properties of the structural alloy. The object of this report was to survey the technical literature to determine the availability of published fracture toughness (K_{Ic}), (K_Q) and stress corrosion (K_{Iscc}) data pertaining to 4340 steel.

RESULTS AND DISCUSSION

Requirement for 4340 Steel

Structural elements in guided missiles utilize ultrahigh-strength alloys to achieve necessary weight savings. The 4340 steel selected for the Copperhead control section housing is a low-alloy, nickel-chromium-molybdenum steel which possesses a good combination of strength and hardness uniformity in large sections and can be welded. Moreover, the alloy can be readily heat treated to ultimate tensile strength levels ranging from 125 to 300 ksi. The yield strength of the Copperhead housing alloy is in the vicinity of 220 ksi. Table 1 shows the chemical composition limits of AISI 4340.

Fracture Toughness and Yield Strength

This alloy is a classical heat-treatable construction metal and is considered a standard against which many other steels are compared. Consequently, 4340 steel has been the subject of investigations since the earliest period of fracture toughness testing.

Much of the past data has been collected by the Metals and Ceramics Information Center and published in its Damage Tolerant Design Handbook.[7] Plane strain

Table 1. CHEMICAL COMPOSITION OF AISI 4340 STEEL (WT. %)

C	0.38-0.43	Si	0.20-0.35
Mn	0.60-0.80	Ni	1.65-2.00
P	0.035 max	Cr	0.70-0.90
S	0.040 max	Mo	0.20-0.30

7. Damage Tolerant Design Handbook, Metals and Ceramic Information Center, Air Force Materials Laboratory, MCIC-HB-01, December 1972, 2nd Supplement, January 1975.

fracture toughness (K_{Ic} or K_Q) data from the Handbook are shown in Figure 1, plotted as function of yield strength of 4340 steel between 200 and 240 ksi. An arbitrary reference line has been drawn on the chart to indicate the generally expected decrease in fracture toughness with increasing yield strengths. A precise rate of decrease cannot be established because of the wide scatter in data points. Many authors present data of this type as a wide band or within envelopes. These data also indicate the feasibility of processing 4340 steel to achieve high toughness along with high strength.

The individual data points in the figure represent mixed results from nine different investigations which are referenced in the Design Handbook.[7] A variety of heat treatments and other test controls were employed in the investigations. This information may be found in the Handbook and will not be repeated here.

For practical comparison, the fracture toughnesses of 4340 alloy removed from three production Spartan second-stage rocket motor cases[8,9] have been incorporated into the chart. In general, the fracture toughness of the motor case material was within the limits expected of 4340 steel. Although the hardnesses

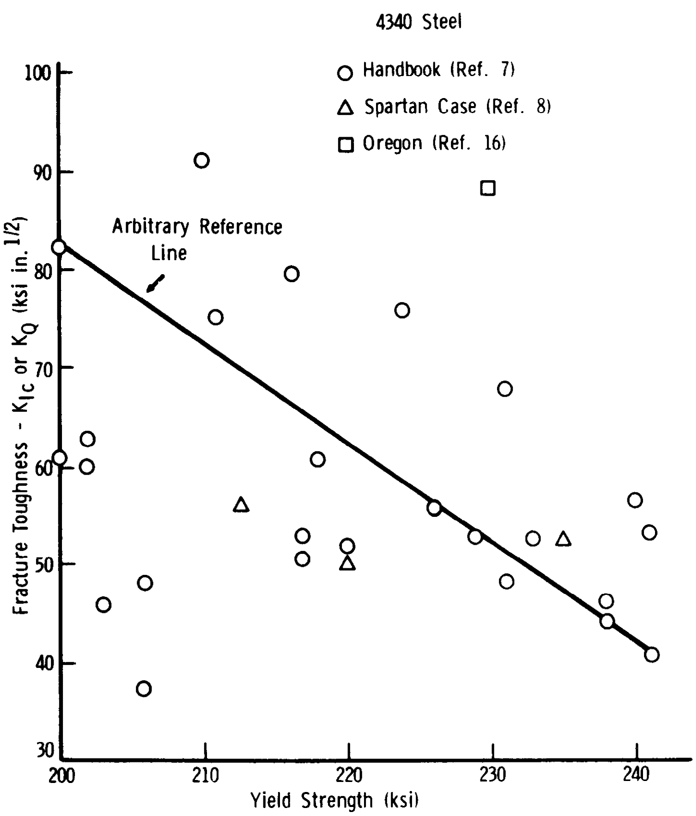

Figure 1. Fracture toughness of 4340 steel.

8. WONG, A. K., LEVY, M., and GRENIS, A. *Stress Corrosion, Mechanical Properties, and Acoustic Emission of 4340 Steel from a Second-Stage Spartan Missile Motor Case.* Army Materials and Mechanics Research Center, report in process.
9. KULA, E. B., and ANCTIL, A. A. *Preliminary Metallurgical Evaluation of Proof Test Failure of Spartan Second-Stage Motor Case.* Army Materials and Mechanics Research Center, AMMRC SP 73-8, May 1973.

of the case materials were similar (~HRC 50), their yield strengths ranged from 212 to 265 ksi and their ultimate tensile strengths ranged from 243 to 272 ksi. Hardness measurements are often used during manufacturing as a quality assurance tool. Care should be taken to insure that the hardness criteria designated for quality control is truly representative of the desired mechanical properties. The motor case yield strengths shown in Figure 1 are based on longitudinal properties. Transverse yield strengths are higher.

Fracture Toughness and Test Specimen Considerations

A host of factors affect the fracture toughness of 4340 alloys of the same strength level. These include testing methodology, temperature, strain rate, impurities and inclusions, fabrication methods, melt practice, and heat treatments.

Many of the data points in Figure 1 represent averaged values from tests of multiple identical specimens. For example, one point located at 53 ksi in.$^{1/2}$ was derived from quantities ranging from 48.6 to 58.6 ksi in.$^{1/2}$. On the other hand, the same investigator also reported identical values of 52.5 ksi in.$^{1/2}$ for three individual specimens in another test. Hence, it appears that the reported fracture toughness data may, at times, vary by more than 20 percent, while at other times it may be perfectly reproducible. Identical specimens and controlled test conditions were used in both cases.

An assortment of test specimens of various sizes and shapes have been designed and used by the workers in the field to measure plane strain fracture toughness. The general appearance and classification of some of these specimens are shown in Figure 2. For the sake of uniformity and reproducibility, the ASTM has standardized[4] the compact tension specimen and the three-point-load bend specimen.

Some of the effects of employing specimens with different geometries and thicknesses are shown in Figure 3,[10,11] evidenced by the scatter in the individual test points. Although the dispersion in the test results can be attributed to the specimen variabilities, it should be noted that it also is typical of the scatter mentioned earlier in tests with identical specimens. Nevertheless, properly designed nonstandard specimens can yield valid data. Figure 3 also exhibits the expected diminution of fracture toughness with increases in yield strength of the 4340 steel.

Experiments have also demonstrated that fracture toughness of 4340 steel increases with increasing test temperatures. Figure 4 shows the changes between -100 F and +200 F for an alloy with a yield strength of about 220 ksi at room temperature.[12] Other data may be found in the Aerospace Structural Metals Handbook.

10. AMATEAU, M. F., and STEIGERWALD, E. A. *Fracture Characteristics of Structural Metals.* TRW, Bureau of Naval Weapons, ER 5937, April 1964.
11. FITZGIBBON, D. P. *Semiannual Report on Pressure Vessel Design Criteria.* Space Technology Laboratories, Inc., Air Force Ballistic Missile Division, TR-59-0000-00714, June 1959.
12. STEIGERWALD, E. A. *Plane Strain Fracture Toughness Data for Handbook Presentation.* TRW, AFML-TR, June 1967 (AD 821626).

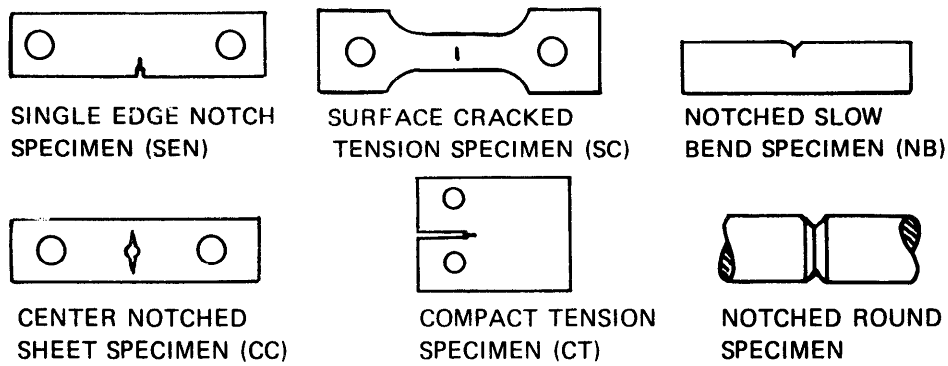

Figure 2. Common specimen geometries for plane strain fracture toughness testing.

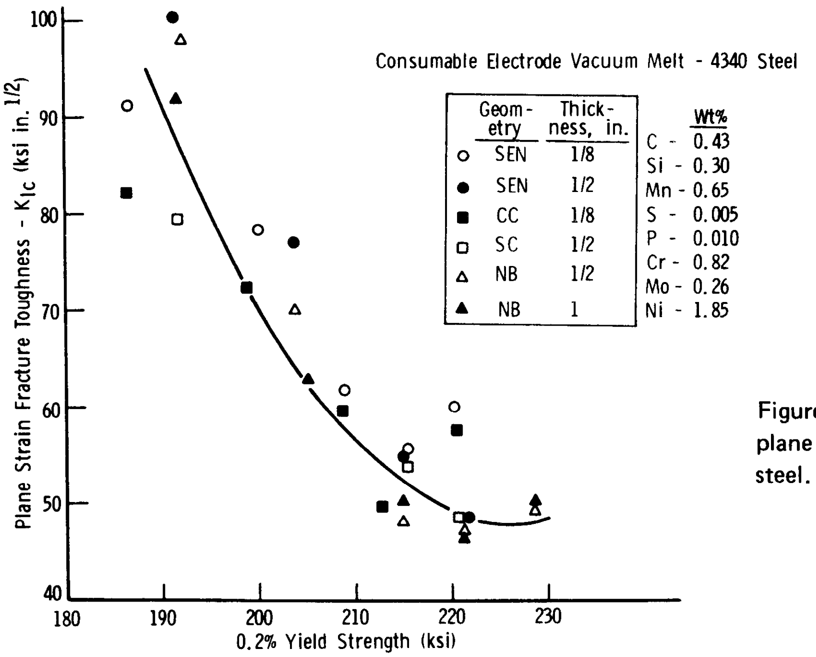

Figure 3. Specimen geometry effects on plane strain fracture toughness of 4340 steel.

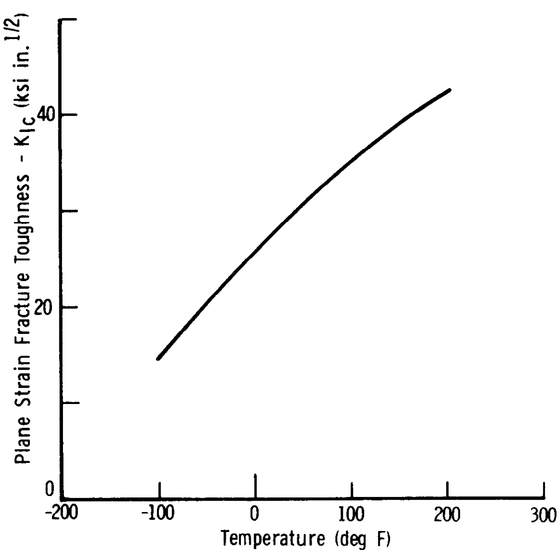

Figure 4. Temperature effect on fracture toughness of 4340 steel.

Fracture Toughness - Processing Effects

Melting practice, impurity elements and inclusions, and heat treatment are other factors which strongly influence fracture toughness of 4340 steel. Table 2 lists some toughness data obtained from heats produced by three conventional melting procedures.[13] Air-melted material exhibited a fracture toughness level of 40.5 ksi in.$^{1/2}$, whereas degassed and vacuum arc remelt (VAR) heats exhibited properties in the ranges of 48.3 to 53.0 and 53.2 to 56.8, respectively.[13] Thus, it appears that vacuum melting can upgrade fracture toughness.

A variety of heat treat procedures are used to achieve desired characteristics. Effects of tempering temperature on fracture toughness[10,11,14] are shown in Figures 5 and 6. Although the toughness generally increases with increasing tempering temperatures, it should be noted that the final selection of tempering temperatures may be based on the need for certain tensile properties, hence, the requirements for a given tensile strength will govern the fracture toughness of the alloy. Austenitizing is also a critical step. Low austenitizing temperatures are preferred because of the resultant small austenite grain size and best combination of mechanical properties; but investigations[15] revealed that the low temperatures did not provide maximum toughness.

Figure 6 also presents the deleterious effect of sulfur-plus-phosphorus content on toughness. Increasing the impurity elements from 0.01% to 0.05% can halve the fracture toughness. Sulfide inclusions as well as undissolved carbide act as crack nuclei which can drastically lower fracture toughness. Additionally, investigators have established that certain microstructural features such as blocky ferrite, upper bainite, and twinned martensite plates are harmful to toughness. On the other hand, other microstructural constituents such as lower bainite, autotempered martensite, and retained austenite can enhance toughness. By controlling the amounts and distributions of the microstructural constituents, the fracture toughness values of 4340 steel can be raised to the level of 18Ni maraging steel of equivalent yield strengths.[15]

Table 2. EFFECT OF MELT PRACTICE
PLANE STRAIN FRACTURE TOUGHNESS OF 4340 STEEL

Melt Practice	Material Yield Strength (ksi)	Plane Strain Fracture Toughness (ksi in.$^{1/2}$)
Air	241	40.5
Degassed	229	53.0
Degassed	231	48.3
VAR	241	53.2
VAR	240	56.8

13. HAUSER, J. J., and WELLS, M. G. H. *Inclusions in High-Strength Steels, Their Dependence on Processing Variables and Their Effect on Engineering Properties.* Crucible Steel Corp., AFML TR-68-222, August 1968.
14. KULA, E. B., and ANCTIL, A. A. *Tempered Martensite Embrittlement and Fracture Toughness in SAE 4340 Steel.* Journal of Materials, JMLSA, v. 4, no. 4, December 1969, p. 817-841.
15. PARKER, E. R., and ZACKAY, V. F. *Microstructural Features Affecting Fracture Toughness of High Strength Steels.* Engineering Fracture Mechanics, v. 7, no. 3, 1975, p. 371-375.

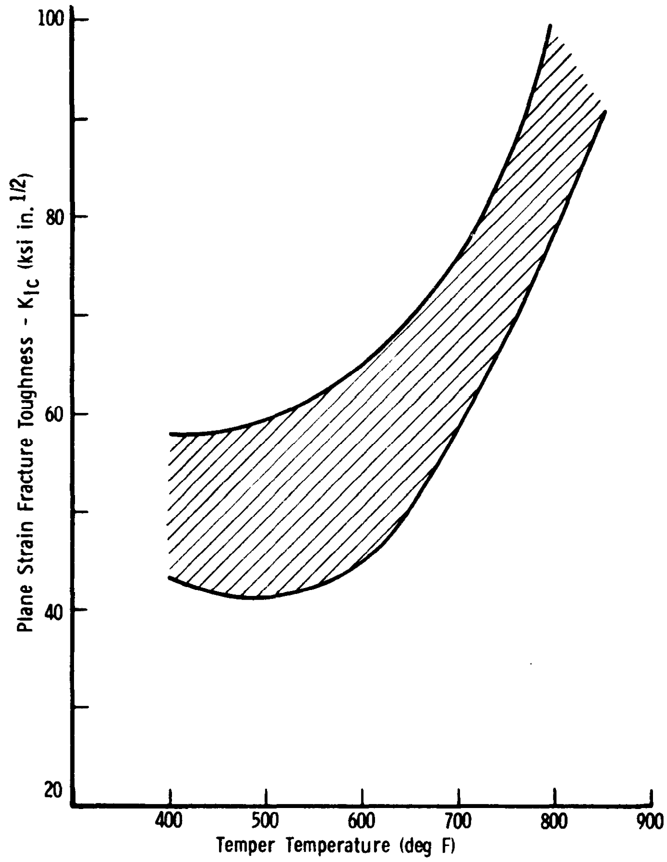

Figure 5. Effect of tempering temperature on fracture toughness on 4340 steel.

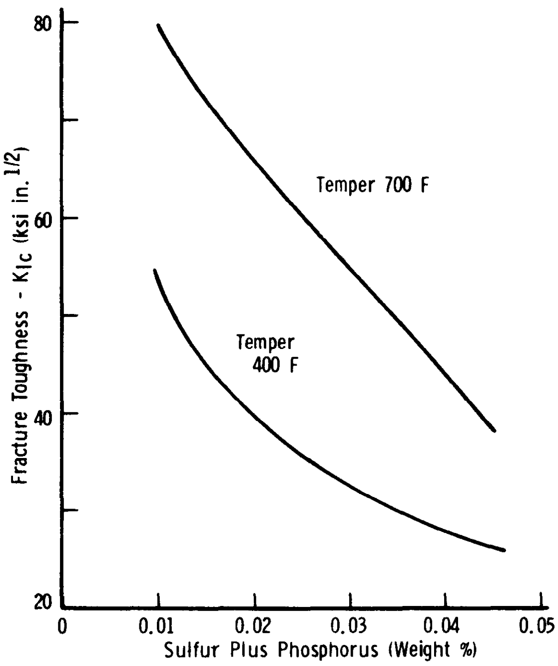

Figure 6. Effect of impurity elements on fracture toughness of 4340 steel.

Heat treatment parameters have also been developed by other workers for improving the microstructure of 4340 steel such that it is possible to achieve fracture toughness of nearly 90 ksi in.$^{1/2}$ at ultimate strength levels of over 300 ksi, thereby enhancing the attraction of the alloy for critical applications. The potential of upgrading the toughness of 4340 steel is indicated in Figure 1 by the fracture toughness value of the alloy specially heat treated to the 230 ksi yield strength level.[16] However, other properties such as resistance to dynamic loading are detrimentally affected and should be investigated.

Fracture Toughness Comparison

Ultrahigh-strength 4340 steel heat treated to have a yield strength over 200 ksi is usually relatively brittle when cracklike defects are present. Nevertheless, it has been used with a modicum of success in the wall of solid propellant rocket motor cases.[8,9] But one noted missile engineer[17] states, with reference to airborne pressure vessels, that commercially standardized grades of steel, e.g., SAE and AISI such as 4340, are generally unsuitable for applications at strength levels above 200 ksi because of their susceptibility to temper embrittlement, quench cracking, and other factors that reduce their resistance to brittle fracture. As a consequence, other specially developed steels should be considered for ultrahigh-strength applications.

As stated earlier, 4340 steel is a classical alloy against which many other materials are compared. Consequently, the literature shows many comparisons of the fracture toughness of 4340 as a function of strength with other candidate ultrahigh-strength steels. Figures 7a and 7b show two comparison graphs of fracture toughness plotted against ultimate tensile strength.[18,19] The ultimate tensile strength of the CLGP housing alloy is above 260 ksi. Similar data from other sources,[20-22] shown in Figures 8a and 8b, are plotted as a function of yield strength. The yield strength of the CLGP housing alloy is about 220 ksi. Some of the toughness data are not considered "valid" because the tests did not meet the requirements of ASTM E399.[4]

Because of the vagaries of materials characteristics and fracture toughness testing, these comparison charts should be approached with caution. However, cursory review indicates that the more costly HP 9-4 and 18% nickel maraging steels are highly promising candidates as alternate materials. Other candidate materials with practical potential include the D6AC and 300M alloys. Table 3 lists the nominal chemical compositions of some ultrahigh-strength steels.

16. WOOD, W. E. *Mechanisms of Enhanced Toughness in Martensitic Alloys.* Oregon Graduate Center, Contract N00019-76-C-0149, April 1977 (AD-A040 373/3GA).
17. HURLICH, A. *Choice of Materials and Fabrication Techniques for Pressure Vessels.* Convair-Astronautics, Chapter 6 in Materials for Missiles and Spacecraft, E. R. Parker, ed., McGraw-Hill Book Co., New York, 1963.
18. Private communication, Lockheed California Company, 1976.
19. McEOWEN, L. J. *Combining Strength and Fracture Toughness.* Metal Progress, March 1975, p. 52.
20. AMATEAU, M. F., and STEIGERWALD, E. A. *Fracture Characteristics of Structural Metals.* TRW, Bureau of Naval Weapons, ER 5937-1, August 1964.
21. *Problems in the Load-Carrying Application of High Strength Steels.* DMIC Report 210, October 1964.
22. MOORE, T. D. *Structural Alloys Handbook.* Mechanical Properties Data Center, Belfour Stulen, Inc., Traverse City, Michigan, 1976.

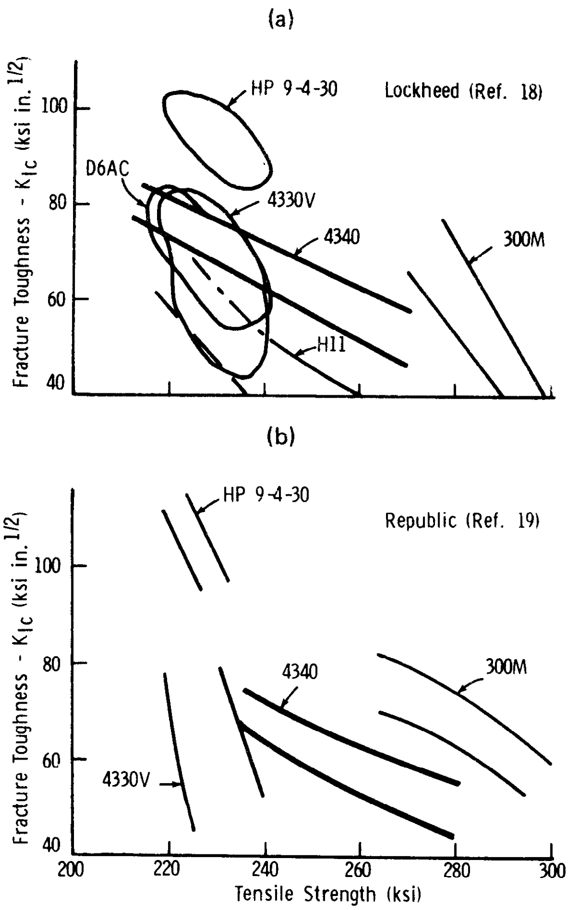

Figure 7. Fracture toughness of ultrahigh-strength steels versus tensile strength.

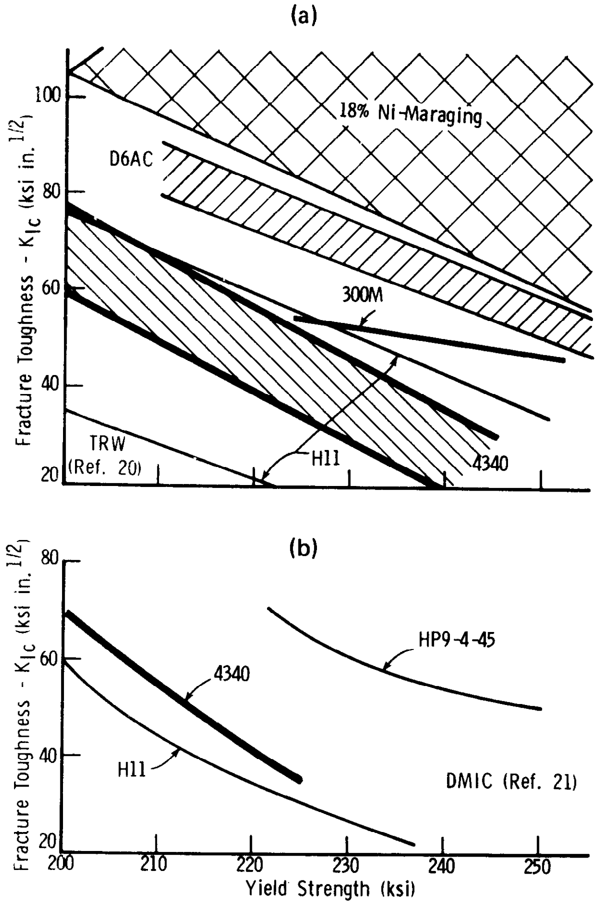

Figure 8. Fracture toughness of ultrahigh-strength steels versus yield strength.

Table 3. NOMINAL COMPOSITIONS OF ULTRAHIGH-STRENGTH STEELS (WT. %)

Designation	C	Mn	Si	Ni	Cr	Mo	V	Co
Low Alloy								
AISI 4340	0.40	0.70	0.30	1.80	0.80	0.25		
AISI 4330V	0.30	0.70	0.30	1.80	0.80	0.25		
AMS 6434	0.35	0.70	0.30	1.80	0.80	0.35	0.20	
D6AC	0.45	0.75	0.25	0.55	1.05	1.00	0.07	
300M	0.42	0.75	1.70	1.80	0.80	0.40	0.80	
Medium Alloy								
AISI H11	0.35	0.30	1.00		5.20		0.40	
High Alloy								
HP 9-4-25	0.25	0.10	0.10	8.50	0.50	0.50	0.10	3.75
HP 9-4-30	0.30	0.30	0.14	8.50	1.00	1.00	0.10	4.50
HP 9-4-45	0.45	0.10	0.10	8.50	0.30	0.20	0.10	3.75
Maraging								
18Ni (200)	0.03	0.10	0.10	18.0		3.25		8.5
18Ni (250)	0.02	0.10	0.10	18.0		4.90		8.0
18Ni (300)	0.03	0.10	0.10	18.5		4.90		9.0

Stress Corrosion Cracking

Stress corrosion cracking of high strength structural alloys was the source of numerous serious problems throughout the Department of Defense during the 1960's.[6] Most of the earlier studies on corrosion cracking were conducted with smooth specimens. However, information of contemporary interest to weapon designers pertains to work with flawed or cracked materials. Fracture mechanics approaches can be used to good advantages in the analysis of stress corrosion cracking of high strength steels.[6,23]

The combined effects of a corrosive environment and a static tensile stress can cause crack initiation, crack propagation at intensities less than K_{Ic}, and eventual failure at stresses below the yield strength of the material. Time-to-failure is strongly influenced by stress intensity. Fracture mechanics plots can be used to display stress corrosion data. Figure 9 shows the effect of initial stress intensity K_{Ii} on time-to-failure of a 4340 steel with an ultimate tensile strength of 235 ksi.

Precracked specimens were used in the development of the stress corrosion data because they eliminated the uncertainties associated with the growth of cracks from corrosion pits. Furthermore, the crack provided a flaw geometry for which a stress analysis was available through fracture mechanics. These tests then produced stress corrosion information that was useful for predicting the behavior of large structural components wherein fracture was a critical design factor.

High initial stress intensities encourage subcritical crack growth. The time-to-failure of individual specimens are plotted against the corresponding K_{Ii} level and used to construct the type of curve shown in Figure 9. Susceptibility to crack growth decreases with stress intensity. A minimum K_{Ii} may be established below which stress corrosion cracking will not occur after an arbitrarily selected time. This minimum test duration time varies with different test materials and is often selected as 100 hours for low alloy steels and up to 1000 hours for high alloy steels. The minimum K_{Ii} value is an apparent threshold stress intensity level designated as K_{Iscc}. As indicated in the figure the K_{Iscc} parameter for this particular heat of 4340 in distilled and salt water (3.5% NaCl) is about 22 ksi in.$^{1/2}$.[24]

Stress Corrosion and Yield Strength

Threshold stress intensity factors from eleven investigations[7] are shown plotted in Figure 10 as a function of yield strength of 4340 steels between 200 and 245 ksi. An arbitrary reference line was drawn through the data to indicate a possible trend. As alluded to by the reference curve, K_{Iscc} values appear to decrease in general with increasing yield strength of the alloy. However, they may level off and remain relatively constant at strength levels above $\sim$230 ksi. Also included in this chart for comparison is an envelope of K_{Ic} fracture toughness data derived from Figure 1.

23. *Stress Corrosion Testing.* ASTM Special Technical Publication 425, 1966.
24. BENJAMIN, W. D., and STEIGERWALD, E. A. *Environmentally Induced Delayed Failures in Martensitic High-Strength Steels.* TRW, AFML TR 68-80, April 1968.

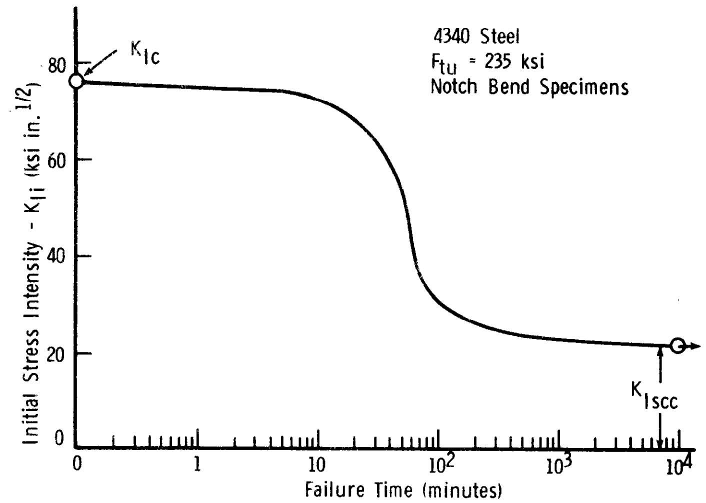

Figure 9. Delayed failure of 4340 steel in distilled and salt water.

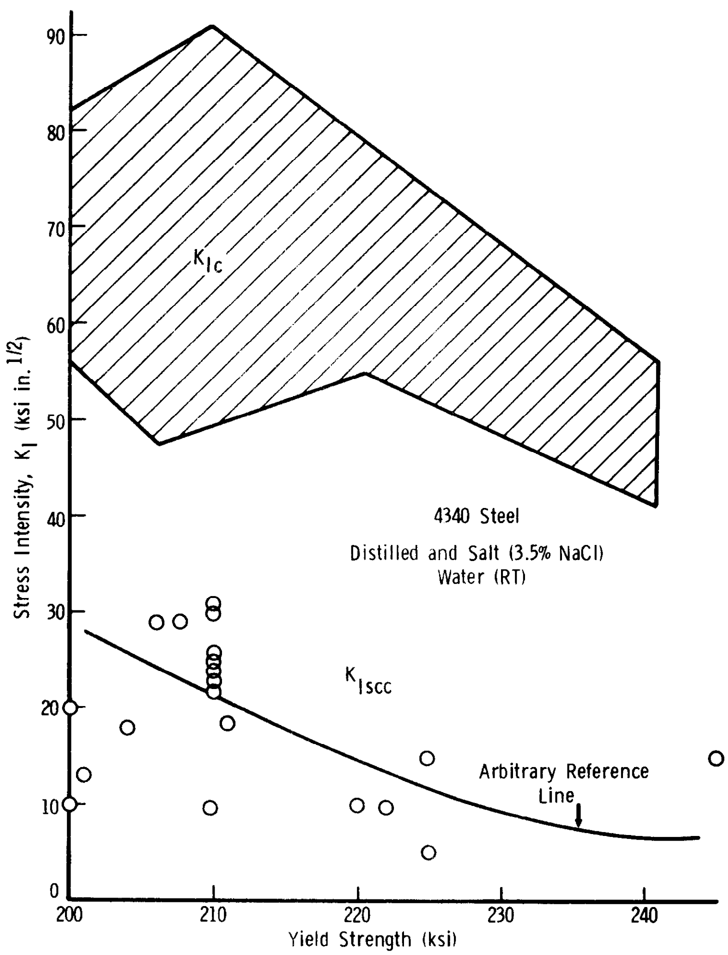

Figure 10. Stress-corrosion resistance and fracture toughness of 4340 steel.

Stress corrosion tests on 4340 steel from Spartan motor cases[8] correlated well with the data shown in Figure 10. From motor case samples with yield strengths of 212 and 219 ksi, K_{Iscc} values of 22 and 17 ksi in.$^{1/2}$, respectively, were determined.

Stress Corrosion and Temperature

Data shown in Figure 10 are for tests conducted at room temperature. At elevated temperatures, the K_{Iscc} parameters for steels usually decrease.[25,26] This influence of temperature is exhibited in Figure 11 for a 4340 steel exposed to temperatures between 32 and 212 F. Also indicated in the chart is the increase of K_{Iscc} at lower test temperatures. The significant decrement in K_{Iscc} between 75 and 212 F emphasizes the need to consider the influence of temperature on the long-term storability of missile components.

Stress Corrosion and Other Variables

Inspection of the K_{Iscc} behavior in Figure 10 and other review sources[6] shows divergence in the data points that is indicative of variables other than yield strength. For example, at the yield strength level of about 210 ksi, the K_{Iscc} of 4340 steel reportedly ranges from nearly 10 to over 30 ksi in.$^{1/2}$.

Factors affecting threshold stress intensity parameter measurements include test methodology,[6,23,27] alloying elements,[28,29] fabrication methods, melt practice,[30] and heat treatments. Although stress corrosion cracks generally propagate intergranularly, there appears to be no significant effects of grain size on K_{Iscc} in 4340 steel. But crack growth rates have been observed to decrease with decreasing grain size,[31,32] a factor which may be important in the selection of heat treatments for 4340 steels destined for long-term storage.

In view of the number of interacting variables capable of influencing the K_{Iscc} parameter, general published stress corrosion data pertaining to 4340 steel should not be used in critical designs without distinct knowledge of the background and history of the material. Stress corrosion tests should be carried out on samples possessing properties closely simulating the condition of the final product.

25. STEIGERWALD, E. A., and HANNA, G. L. *Influence of Environment on Crack Propagation and Delayed Failures in High Strength Steels.* TRW, AFML RTD-TDR-63-4225, January 1964.
26. KORTOVICH, C. *Corrosion Fatigue Behavior of 4340 and D6AC Steels Below K_{Iscc}.* TRW, Report ER 7717, April 1974.
27. STEIGERWALD, E. A., and BENJAMIN, W. D. *Stress Corrosion Cracking Mechanisms in Martensitic High Strength Steels.* TRW, AFML TR 67-98, April 1967.
28. TINER, N. A., and GILPIN, C. B. *Microprocesses in Stress Corrosion of Martensitic Steels.* Corrosion, v. 22, October 1966, p. 271.
29. SANDOZ, G. *The Effects of Alloying Elements on the Susceptibility to Stress Corrosion Cracking of Martensitic Steels in Salt Water.* Met. Trans., v. 2, 1971, p. 1055.
30. CARTER, C. S. *The Effect of Silicon on the Stress Corrosion Resistance of Low-Alloy High-Strength Steels.* Corrosion, v. 25, no. 10, October 1969, p. 423.
31. PROCTER, R., and PAXTON, H. *The Effect of Prior Austenite Grain Size on the Stress Corrosion Susceptibility of AISI 4340 Steel.* ASM Trans. Quart., v. 62, no. 4, December 1969, p. 989.
32. WEBSTER, D. *Effect of Grain Refinement on the Microstructure and Properties of 4340M Steel.* Boeing Document D6-25220, The Boeing Company, Seattle, Washington, April 1970.

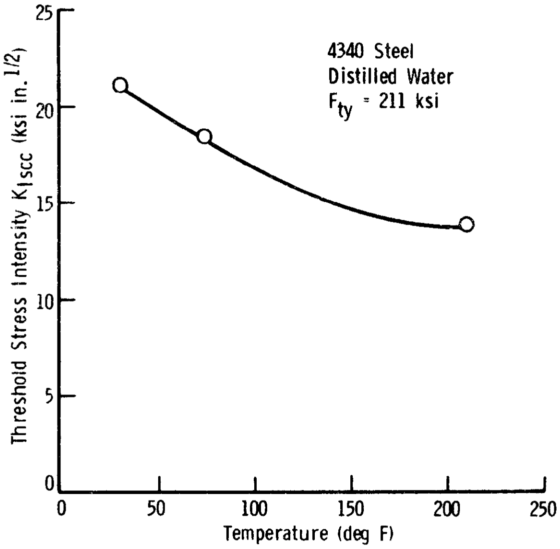

Figure 11. Effect of temperature on K_{Iscc} of 4340 steel.

Environmental Effects

As mentioned earlier, the stress corrosion behavior shown in Figure 10 is for 4340 steel in both distilled and salt water environments. Several experiments[24,27,33] have demonstrated that stress corrosion tests of high strength steels in 2% to 4% NaCl solution environment yields K_{Iscc} data similar to that derived from tests in distilled water. Furthermore, other laboratory salt water studies have been made[34,35] which reveal good correlation of data with tests in flowing sea water environments. Therefore, it can be generally assumed that tests in either of the three environments will yield similar results.

Other aggressive environments can also motivate stress corrosion in 4340 steels. In a salt water and acetic acid solution saturated with H_2S,[36] the K_{Iscc} values of 4340 steels fall within the lower bounds of the K_{Iscc} data shown in Figure 10. On the other hand, the alloy is also susceptible to a methanol environment, but its K_{Iscc} value is somewhat higher than that observed in salt water solutions. Similar behavior has been observed in tests with butyl alcohol and acetone.[33]

Large changes in acidity and salt concentration of aqueous environments do not appreciably affect K_{Iscc}. The introduction of H_2S appears to lower K_{Iscc} to the lowest values reported for a particular type of steel in salt water.[37] Thus it appears that in critical applications, an analysis should be made of all fluids

33. TANIGUCHI, N., and TROIANO, A. *Stress Corrosion Cracking of 4340 Steels in Different Environments.* Trans. Iron Steel Inst., Japan, v. 9, no. 4, 1969.
34. LENNOX, T. J., et al. *Marine Corrosion Studies: Stress Corrosion Cracking Deep Ocean Technology Cathodic Protection on Fatigue.* Naval Research Laboratory, NRL Memorandum Report 1711, May 1966.
35. SANDOZ, G., and NEWBEGIN, R. *A Comparison of Laboratory Salt Water and Flowing Natural Seawater as an Environment for Tests of Stress Corrosion Cracking Susceptibility.* Report of NRL Progress, Naval Research Laboratory, May 1969.
36. SNAPE, E. *Stress-Induced Failure of High Strength Steels in Environments Containing Hydrogen Sulphide.* Br. Corrosion J., v. 4, no. 5, September 1969, p. 252.
37. BUCCI, R., PARIS, P., LOUSHIN, L., and JOHNSON, H. *Fracture Mechanics Consideration of Hydrogen Sulfide Cracking in High Strength Steels, Stress Analysis and Growth of Cracks.* Proceedings of the 1971 National Symposium on Fracture Mechanics, Part 1, ASTM STP 513, Philadelphia, PA, 1972.

and compounds used in the various steps of processing and packaging to insure the absence of any substance capable of promoting stress corrosion cracking, particularly during long terms of storage in a damp environment.

Missile Storage Criteria - Humidity Effects

Experimental data is needed for the establishment of realistic criteria for environmental control during missile storage. It is common practice[38] to assume that a maximum allowable relative humidity of 50% and a temperature range of 70 F to 85 F provide an adequate environment for the prevention of corrosion in metal parts. However, limited studies of 4340 steel with yield strengths of about 220 ksi indicate premature failure both in 90% relative humidity at 75 F[39] and in 50% relative humidity environments at 90 F and 120 F. In the 50% relative humidity environment under a stress intensity 75% of K_{Ic} (K_{Ic} = $\sim$52 ksi in.$^{1/2}$), the 4340 steel in the 90 F surroundings fractured in 31 days and at 120 F fractured in 12 days.[38] More information is needed to elucidate the stress corrosion behavior of 4340 steels in humid environments which simulate missile storage conditions.

Stress Corrosion Comparison

Cursory review of mixed stress corrosion cracking data[6] indicates that within the 200 to 250 ksi yield strength range, steels with K_{Iscc} parameter better than 4340 steel include: HP 9-4 in the 200 ksi region and D6AC in the 200 to 230 ksi range. Otherwise, 4340 steels appear to be as good or better than most steels within the broader 200 to 250 ksi range. Generally, stress corrosion cracking susceptibility decreases in these alloys at lower yield strength levels.

SUMMARY

1. Fracture toughness and stress corrosion data pertaining to 4340 steel are generally available in the technical literature.

2. Many factors affect the data, including test methodology, composition, melt practice, fabrication, heat treatment, and environments.

3. For applications in critical materiel, mechanical properties data must be obtained from material samples treated to incorporate characteristics closely resembling those of the finished product.

4. Data are needed to establish the stress corrosion behavior of 4340 steel to provide a sound basis for specifying missile storage conditions.

5. Higher fracture toughness and stress corrosion cracking resistance may be achieved through the designation of 4340 steels with lower levels of yield strengths.

38. Private communication: R. G. Britton, C. Austin, U. S. Army Missile R&D Command, Huntsville, Alabama, September 14, 1977.
39. CARTER, C. S. *The Effect of Silicon on the Stress Corrosion Resistance of Low-Alloy High-Strength Steels.* The Boeing Company, Research Report D6-23872, ARPA Contract N00014-66-C-0365, March 1965.

LITERATURE CITED

1. *Fracture Toughness Testing and Its Applications* ASTM STP 381, 1965.
2. *Plane Strain Crack Toughness Testing of High Strength Metallic Materials.* ASTM STP 410, 1966.
3. *Review of Developments in Plane Strain Fracture Toughness Testing.* ASTM STP 463, 1970.
4. ASTM Test for Plane-Strain Fracture Toughness of Metallic Materials: E399-74.
5. SCULLY, J. C., ed. *The Theory of Stress Corrosion Cracking in Alloys.* NATO Science Committee, Research Evaluation Conference, Brussels, W. S. Maney and Sons, Ltd., Leeds, England, 1971.
6. BROWN, B. F., ed. *Stress Corrosion Cracking in High Strength Steel, Titanium, and Aluminum Alloys.* U. S. Government Printing Office, Stock No. 0851-0058, 1972.
7. Damage Tolerant Design Handbook, Metals and Ceramic Information Center, Air Force Materials Laboratory, MCIC-HB-01, December 1972, 2nd Supplement, January 1975.
8. WONG, A. K., LEVY, M., and GRENIS, A. *Stress Corrosion, Mechanical Properties, and Acoustic Emission of 4340 Steel from a Second-Stage Spartan Missile Motor Case.* Army Materials and Mechanics Research Center, report in process.
9. KULA, E. B., and ANCTIL, A. A. *Preliminary Metallurgical Evaluation of Proof Test Failure of Spartan Second-Stage Motor Case.* Army Materials and Mechanics Research Center, AMMRC SP 73-8, May 1973.
10. AMATEAU, M. F., and STEIGERWALD, E. A. *Fracture Characteristics of Structural Metals.* TRW, Bureau of Naval Weapons, ER 5937, April 1964.
11. FITZGIBBON, D. P. *Semiannual Report on Pressure Vessel Design Criteria.* Space Technology Laboratories, Inc., Air Force Ballistic Missile Division, TR-59-0000-00714, June 1959.
12. STEIGERWALD, E. A. *Plane Strain Fracture Toughness Data for Handbook Presentation.* TRW, AFML-TR, June 1967 (AD 821626).
13. HAUSER, J. J., and WELLS, M. G. H. *Inclusions in High-Strength Steels, Their Dependence on Processing Variables and Their Effect on Engineering Properties.* Crucible Steel Corp., AFML TR-68-222, August 1968.
14. KULA, E. B., and ANCTIL, A. A. *Tempered Martensite Embrittlement and Fracture Toughness in SAE 4340 Steel.* Journal of Materials, JMLSA, v. 4, no. 4, December 1969, p. 817-841.
15. PARKER, E. R., and ZACKAY, V. F. *Microstructural Features Affecting Fracture Toughness of High Strength Steels.* Engineering Fracture Mechanics, v. 7, no. 3, 1975, p. 371-375.
16. WOOD, W. E. *Mechanisms of Enhanced Toughness in Martensitic Alloys.* Oregon Graduate Center, Contract N00019-76-C-0149, April 1977 (AD-A040 373/3GA).
17. HURLICH, A. *Choice of Materials and Fabrication Techniques for Pressure Vessels.* Convair-Astronautics, Chapter 6 in Materials for Missiles and Spacecraft, E. R. Parker, ed., McGraw-Hill Book Co., New York, 1963.
18. Private communication, Lockheed California Company, 1976.
19. McEOWEN, L. J. *Combining Strength and Fracture Toughness.* Metal Progress, March 1975, p. 52.
20. AMATEAU, M. F., and STEIGERWALD, E. A. *Fracture Characteristics of Structural Metals.* TRW, Bureau of Naval Weapons, ER 5937-1, August 1964.
21. *Problems in the Load-Carrying Application of High Strength Steels.* DMIC Report 210, October 1964.
22. MOORE, T. D. *Structural Alloys Handbook.* Mechanical Properties Data Center, Belfour Stulen, Inc., Traverse City, Michigan, 1976.
23. *Stress Corrosion Testing.* ASTM Special Technical Publication 425, 1966.
24. BENJAMIN, W. D., and STEIGERWALD, E. A. *Environmentally Induced Delayed Failures in Martensitic High-Strength Steels.* TRW, AFML TR 68-80, April 1968.
25. STEIGERWALD, E. A., and HANNA, G. L. *Influence of Environment on Crack Propagation and Delayed Failures in High Strength Steels.* TRW, AFML RTD-TDR-63-4225, January 1964.
26. KORTOVICH, C. *Corrosion Fatigue Behavior of 4340 and D6AC Steels Below K_{Iscc}.* TRW, Report ER 7717, April 1974.
27. STEIGERWALD, E. A., and BENJAMIN, W. D. *Stress Corrosion Cracking Mechanisms in Martensitic High Strength Steels.* TRW, AFML TR 67-98, April 1967.
28. TINER, N. A., and GILPIN, C. B. *Microprocesses in Stress Corrosion of Martensitic Steels.* Corrosion, v. 22, October 1966, p. 271.
29. SANDOZ, G. *The Effects of Alloying Elements on the Susceptibility to Stress Corrosion Cracking of Martensitic Steels in Salt Water.* Met. Trans., v. 2, 1971, p. 1055.
30. CARTER, C. S. *The Effect of Silicon on the Stress Corrosion Resistance of Low-Alloy High-Strength Steels.* Corrosion, v. 25, no. 10, October 1969, p. 423.
31. PROCTER, R., and PAXTON, H. *The Effect of Prior Austenite Grain Size on the Stress Corrosion Susceptibility of AISI 4340 Steel.* ASM Trans. Quart., v. 62, no. 4, December 1969, p. 989.
32. WEBSTER, D. *Effect of Grain Refinement on the Microstructure and Properties of 4340M Steel.* Boeing Document D6-25220, The Boeing Company, Seattle, Washington, April 1970.
33. TANIGUCHI, N., and TROIANO, A. *Stress Corrosion Cracking of 4340 Steels in Different Environments.* Trans. Iron Steel Inst., Japan, v. 9, no. 4, 1969.
34. LENNOX, T. J., et al. *Marine Corrosion Studies: Stress Corrosion Cracking Deep Ocean Technology Cathodic Protection on Fatigue.* Naval Research Laboratory, NRL Memorandum Report 1711, May 1966.
35. SANDOZ, G., and NEWBEGIN, R. *A Comparison of Laboratory Salt Water and Flowing Natural Seawater as an Environment for Tests of Stress Corrosion Cracking Susceptibility.* Report of NRL Progress, Naval Research Laboratory, May 1969.
36. SNAPE, E. *Stress-Induced Failure of High Strength Steels in Environments Containing Hydrogen Sulphide.* Br. Corrosion J., v. 4, no. 5, September 1969, p. 252.
37. BUCCI, R., PARIS, P., LOUSHIN, L., and JOHNSON, H. *Fracture Mechanics Consideration of Hydrogen Sulfide Cracking in High Strength Steels, Stress Analysis and Growth of Cracks.* Proceedings of the 1971 National Symposium on Fracture Mechanics, Part 1, ASTM STP 513, Philadelphia, PA, 1972.
38. Private communication: R. G. Britton, C. Austin, U. S. Army Missile R&D Command, Huntsville, Alabama, September 14, 1977.
39. CARTER, C. S. *The Effect of Silicon on the Stress Corrosion Resistance of Low-Alloy High-Strength Steels.* The Boeing Company, Research Report D6-23872, ARPA Contract N00014-66-C-0365, March 1965.